Evaluation of the one-step Lumicyano™ used in the visualisation of fingermarks on fabrics

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Abstract

This study consisted of three parts to evaluate the performance of Lumicyano™ on a variety of fabrics. One part assessed the impact of dye percentage (8%, 9% and 10%) on visualisation of fingermark detail and luminescent brightness in split grab marks. A 9% dye produced the highest quality detail of grab impressions with least interference from background fluorescence. The second part investigated the optimal relative humidity (RH, 75-84%) for certain fabric types using Lumicyano on split, six-series depletion fingermarks. It was concluded that the recommended RH of 80% remained the ideal cyanoacrylate fuming environment. The final and third part of this study determined the impact of sequential addition of Basic Yellow 40 (BY40) on Lumicyano compared to traditional cyanoacrylate (CA) followed with BY40 application. Results from this study demonstrated that Lumicyano on its own developed fingermarks with superior quality to Lumicyano with sequential addition of BY40 or traditional cyanoacrylate followed by BY40. Inclusion of more fabrics, donors and longer ageing periods should be explored in future studies to determine what frameworks are best for certain types of fabrics.

Keywords:

Cyanoacrylate fuming; Lumicyano; Dye; Humidity; Fabrics

1 Introduction

Since possibly as early as 300 B.C.E fingermarks have been a means of identifying persons [1-3]. The value of a fingermark has been known and utilised as a signature; unique and one-of-a-kind. Databases such as IDENT1, formerly known as the National Automated Fingerprint Identification System (NAFIS), in the United Kingdom or the Integrated Automated Fingerprint Identification System (IAFIS) in the United States are capable of providing possible matches between known and unknown scene marks [1]. Palmprints, as noted by several authors, are large and can contain ample information for identification [4-7] and account for about 20-30% of crime scene marks recovered[4,8-10].

Identification of fingermarks is made according to Level I (pattern types), Level II (minutiae) and Level III (pores) details in fingerprints and marks, as well as supplementary information such as wrinkles, flexion creases [5, 8, 11-15] and datum points [7] in palmprints. These details combine to form a unique, unchanging pattern [16-18]. However, if the dermal layer, comprised of structural and supportive tissues, is damaged by scarring, burning or some other means [3, 16, 17] this can alter the palmprint. Nevertheless, damage to the dermal layer can contribute unique features to patterns that may result in identification. The odds of two individuals, even twins, having identical fingerprints is minute [3, 16, 17, 19]. In terms of intelligence gathering, fingermark patterns and palmprints can be extremely valuable to ascertain where a mark has been placed even if identification may not be possible due to lack of quality. Pinpointing the location of a mark can help corroborate events or potentially lead to a deoxyribonucleic acid (DNA) profile if the area is targeted for such analysis [20].

A well-established method for developing latent fingermarks is cyanoacrylate (CA) fuming where the fingermark comes into contact with ethyl-cyanoacrylate vapour (ECA). Wargacki *et al*. [21] postulate that polymerization of cyanoacrylates is initiated by components within eccrine sweat, particularly lactate ions and that water is not responsible for initiation of cyanoacrylate polymerisation, but rather its evaporation is likely a major contributor to fingermark susceptibility to decay by airflow [21-23]. Wargacki *et al*. [23] note marks aged over seven days that were not exposed to light or airflow as comparable in quality to freshly deposited fingermarks. The ECA preferentially polymerises on residues deposited by finger or palm ridges [22], while the background or substrate remains relatively free of any polymerisation. This produces the contrast vital to fingermark enhancement and examination [21, 23-24]. However, if a substrate is similarly coloured to the polymerised CA, a secondary technique can be employed to provide the necessary contrast [21, 25], such as powdering or basic yellow 40 (BY40). This addition of chemicals in the case of BY40 however, can have a detrimental impact on the visualised mark, which developers have responded to by creating one-step cyanoacrylates, which incorporate a dye within the cyanoacrylate. One available on the market is Lumicyano™ (Crime Science Technology [CST], France). Although it is more expensive than the traditional variety of cyanoacrylates, it has the advantage of eliminating a second step and very well may be a better alternative [26-28]. Farrugia *et al*. [27] investigated the development of fingermarks on plastic carrier bags using Lumicyano. In one trial, a 4% Lumicyano solution with the sequential application of Basic Yellow 40 (BY40) detected additional marks when compared to the traditional two-step method [27], while Lumicyano Solution sans Lumicyano Powder with sequential application of BY40 was also used, and though essentially the same as the traditional method, this method revealed 16% more latent fingermarks than the traditional two-step method, thus indicating that the Lumicyano Solution itself may be superior to other cyanoacrylates used. The enhanced visualisation of fingermarks and superior development of polymer morphology by Lumicyano over traditional cyanoacrylates found in this study is consistent with that reported by Prete *et al*. [25] and Groeneveld *et al*. [29]. Moreover, it was noted here, as well as in another study performed by Farrugia *et al*. [28], that Lumicyano fluoresced better on light coloured items prior to BY40 application, but any difference in fluorescence was minimal after its application. The manufacturer states that images of treated material should be taken within 48 hours of fuming as there can be dramatic decreases in fluorescence despite initial strength of fluorescence immediately after fuming and prompt examination. This was observed in the Farrugia *et al.* (2014) study where it was observed that the fluorescence was hard to see even after one day “to the extent that it was a strain on the operator's eye and could potentially be missed” [28].

As most studies involving Lumicyano have been conducted on non- or semi-porous substrates, there was an interest to perform several studies on porous materials such as fabrics. In 2013, Fraser *et al*. [30] compared the visualisation of fingermarks on fabrics using vacuum metal deposition (VMD) to cyanoacrylate fuming (CAF). VMD visualised marks better than the CAF method, which is the opposite of what had been previously discovered with non- and semi-porous substrates. Between different fabric types, there were varying degrees of ridge detail developed after either method, attributed to different weave types and levels of porosity. Fraser *et al*. [20] and Knighting *et al*. [31] agree that, despite the fabric type, what affects the ability to retrieve detailed fingermarks is the donor, as all donors have different abilities to produce residues. Additionally, environmental factors affect residue production and/or deposition. Consequently, Knighting *et al*. [31] concede that fabrics are challenging substrates with which to visualise fingermarks.

Paine *et al*. [22] conducted a study, once again using a non-porous substrate (black polypropylene), to investigate the optimal RH in conjunction with CA fuming and concluded that the widely used and recommended 80% RH in fuming cabinets provides the best quality visualisation. Hence, an investigation into the optimal RH for fabrics merited further examination since non-porous and porous substrates have vastly different properties. The aim of this study was to determine the impact of changes in relative humidity on the level of fingermark enhancement using Lumicyano and traditional cyanoacrylate fuming on a variety of fabrics.

2 MATERIALS AND METHODS

2.1 DONORS

Three female and three male donors between 34 and 59 years of age participated in Study 1 and 3, with only three (donors 2-4 [ages 42-54]) involved in Study 2.

2.2 FABRIC

Studies 1 & 3 used black taffeta polyester, white taffeta polyester, black Habotai silk and white Habotai fine silk, while Study 2 additionally used black Silesia cotton, black satin acetate, medium white viscose satin and white nylon fabrics. All fabrics were purchased from Whaleys (Bradford) Ltd, Bradford, except nylon which was purchased from The Fabric Mill at Halley Stevensons, Dundee. Each fabric had a plain weave and thread count of 3 per mm, however, the silk had a more open weave compared to the other fabrics. The fabrics were cut into approximately A5 size swatches (~15 x 21 cm) and labelled with the fabric type, donor number, process day and marks to guide the hand orientation of the donor (Studies 1 & 3) or marks to place the template on (Study 2). All fabrics were used as bought and unwashed so as to simulate new, freshly bought clothing.

2.3 SAMPLE ACQUISITION

Each donor was asked to refrain from hand washing for at least 45 minutes prior to providing a donation, and a minimum of one hour was left between subsequent collections. For collection of Studies 1 & 3 two swatches of randomly selected fabrics were placed on the arm of the investigator wearing a lab coat while the donor was instructed to firmly grab for ten seconds (to simulate a struggle), ensuring that their pointer and ring fingers were positioned in line with the marks drawn on the swatches. Figure 1 illustrates how the swatches were divided into three parts for both studies. Each section was randomly selected for a different dye percentage (Study 1) and development method (Study 3) in order to eliminate error rates derived from optimal or disadvantageous sides. All donors donated on all four fabrics that were then aged for 1, 3, 7, 14, 21 or 28 days. Immediately after sample acquisition, the fabric swatches were placed in plastic wallets set within binders and stored in a locked, dark cabinet at room temperature for the number of days it was set to age. For the collection in Study 2 one male and two female donors participated. Two swatches of randomly selected fabrics were placed on a clipboard and covered with a template (Figure 2). Each donor was instructed to press firmly for no more than three seconds in the appropriate location of the template starting at number one and continuing down to number six using the same finger in a depletion series. Six depletions were decided upon based on the Sears *et al*. paper [32] which explained that on porous substrates little residual matter remains after the sixth finger mark because of absorption by the material. The donors were asked to do this for all ten digits; five on one swatch and five on the other. Four hundred and thirty-two samples were collected (six donors, six different ages, three methods and four fabric types) for Studies 1 & 3.

Meanwhile, a total of 2,880 samples were gathered (a six-series depletion, eight fabric types, three donors, ten humidity levels and two ageing periods) for Study 2.

Figure 1. ***Example of sample divisions for fabric swatches used in Study 1 (a) and Study 3 (b).***

Figure 2. ***Example of template used for fingermark deposits onto samples in humidity study (study 2).***

2.4 CYANOACRYLATE FUMING CHAMBER, CYANOACRYLATE, PHOTOGRAPHY AND FLUORESCENCE

A model number CA305, Air Science fuming chamber with an approximate volume of about 450 litres was used for all three studies. The chamber contains a temperature controlled hot plate that is internally set to 120ºC and a digitally controlled humidifier that had been verified using a digital thermometer (RS 206-3738). For the purpose of Studies 1 & 3, the RH was set to 80%, per recommendation by the Home Office Police Scientific Development Branch of the United Kingdom as cited by Paine *et al*. [22] for both Lumicyano solution and traditional CA. While in Study 2 the humidity levels were changed to a range of 75-84, increasing by one unit each run. All studies had a run time of 40 minutes.

2.4.1 Lumicyano Solution Study 1

When making an 8% solution, Lumicyano Solution (2.0 g) (CST) and Lumicyano Powder (0.16 g) (CST) were mixed in a new, shallow foil dish. For a 9% solution, 2.0 g of solution and 0.18 g of the powder were mixed. Two grams of Lumicyano solution and 0.20 g powder were used to make up a 10% solution. This foil dish was then placed on the heat source in the fuming chamber.

2.4.2 Lumicyano Solution Study 2

All samples were processed using a 9% solution. Samples were cut to split each print thus enabling direct comparisons between humidities with the depletion series; these were then stapled to card and hung by paper fasteners to process all appropriate samples at the same time.

2.4.2 Lumicyano Solution Study 3

A 9% solution was employed for two-thirds of every swatch, with one of these thirds designated for BY40 treatment after fuming. For those selected, BY40 (1 g) (Sirchie®) was mixed with 500 mL of ethanol (Fischer Scientific) to make a BY40 solution. This was applied to individual swatches for one minute followed by a wash with water. Subsequently, swatches were allowed to air dry before being photographed on the same day of dyeing.

2.4.3 Cyanoacrylate Solution Study 3

Cyanoacrylate (2.0 g) (CSI Equipment Ltd, U.K.) was used instead of Lumicyano on the final third of each sample, allowed to set and then treated the following day with BY40. Photography took place the same days as BY40 treatment.

The manufacturer instructions for Lumicyano state the use of a 4% mixture, but it was suggested online by the manufacturer [33] that an 8% mixture may visualise more marks and do so more effectively, therefore 8% was the minimum percentage of dye used in these studies.

2.5 SAMPLE EXAMINATION

A Mason Vactron Quaser 2000/30 at a wavelength range of 468-526 nm (Lumicyano treated samples) and 400-469 nm (BY40 treated samples) was used to perform fluorescence examination in all studies in conjunction with a Nikon Digital Camera D5100 using an NIKKOR 18-55 mm Nikon lens attached to an orange filter (Schott OG550, Lumicyano) and yellow filter (Schott GG495, BY40 treated samples). A Micro NIKKOR 40 mm Nikon lens with an orange filter (Schott OG550) was used for close-up images of select fingerprints in Study 2. Viewing for all samples was performed with orange Schott OG550 (Lumicyano) and GG495 (BY40) (Mason Vactron) goggles for protection. All samples were illuminated from the same distance (approximately 30 cm) to help inform on the impact of dye concentration on observed fluorescence, ridge detail and grading of a fingermark. All Lumicyano photographs were taken on the day of fuming, while those treated with BY40 were photographed the day after BY40 treatment. All photographs of the samples were taken using a copy stand at a distance of approximately 10-25 cm, depending on the size of the sample and whether close up images were to be taken. An aperture of f10, with shutter speeds dependent on the sample being photographed (darker samples took longer for the shutter to trigger than lighter fabrics). None of the photographs taken were digitally enhanced, though the separately photographed samples (Figures 4, 5, 7, 11, 13, 14 and 15) were joined together, using Microsoft tools to allow direct comparisons of results.

2.6 Evaluation of Grab Marks of Study

Fluorescence examination was performed and grab marks were evaluated using a modified combination of the University of Lausanne (UNIL) and CAST grading scheme, due to the inclusion of palm detail and to differentiate the level of detail within a grade [Table 1]. As the grading can allow for marks of quite different detail to fall within the same grade, the fingermark grades were converted to numerical values using Table 1, this in turn would allow the determination of the highest scoring or optimal method, as well as to more easily allow for statistical analysis. All marks were graded by one individual who is not a fingermark expert. However, a representative portion of the samples were verified and agreed by a second fingermark researcher with considerable experience in fingermark research.

Table 1. ***Modified CAST and UNIL grading scheme (adapted from 34 with scoring used to allow for detail observed within a grade to be defined, + (Clearly more visible ridges, but not enough to be a higher grade), ± (Ridges that are slightly visible but not sufficient to be a + or next full grade) and – (Less detail than a full grade).***

Detail visualised	Grade	Score
No development	0	0.00
Signs of contact but <1/3 of mark with continuous ridges	1 -	0.75
	1	1
	1 ±	1.25
	1 +	1.5
1/3-2/3 of mark with continuous ridges	2 -	1.75
	2	2
	2 ±	2.25
	2 +	2.5
>2/3 of mark with continuous ridges, but not quite a perfect mark	3 -	2.75
	3	3
	3 ±	3.25

	3 +	3.5
Full development – whole mark clear with continuous ridges	4 -	3.75
	4	4
	4 ±	4.25
	4 +	4.5

2.7 STATISTICAL ANALYSIS

3 FINGERMARKS PRODUCED BY DIFFERENT DONORS OR EVEN THE SAME DONOR ARE SUBJECT TO A PLETHORA OF BIOLOGICAL AND ENVIRONMENTAL FACTORS SUCH AS AGE, SEX, TIME OF DAY AND ACTIVITY LEVEL, MAKING DONOR ABILITY TO PRODUCE RETRIEVABLE FINGERMARKS INCONSTANT [20]. CONSEQUENTLY, THE GENERALISED LINEAR MODEL OR A GENERALISED MIXED MODEL WERE USED TO TEST FOR SIGNIFICANT EFFECTS OF A VARIETY OF INDEPENDENT VARIABLES ON FINGERMARK DEVELOPMENT. THE GENERALISED LINEAR MODEL AND GENERALISED LINEAR MIXED MODELS ARE SUITABLE WHERE THE DEPENDENT VARIABLE IS NON-NORMAL SUCH AS IN THIS CASE WHERE THE FINGERMARK GRADE FOLLOWS A MULTINOMIAL (ORDINAL) DISTRIBUTION, AND THE REGRESSION REQUIRES A CUMULATIVE LOGIT AS A LINK FUNCTION. FOR STUDY 1, THE ANALYSIS EXAMINED THE MAIN EFFECTS OF AND INTERACTION BETWEEN TWO FACTORS, DYE PERCENTAGE AND AGEING PERIOD, ON FINGERMARK SCORE. STUDY 2 EXPLORED THE MAIN EFFECTS AND INTERACTION OF FACTORS, DEVELOPING RH AND AGEING PERIOD, ON FINGERMARK SCORE FROM THE FIRST OF THE SIX-SERIES DEPLETION AND STUDY 3 EXAMINED THE MAIN EFFECTS AND INTERACTION OF TECHNIQUE AND AGEING PERIOD FACTORS. RESULTS & DISCUSSION

3.1 STUDY 1. DYE STUDY

The aim of Study 1 was to determine whether an 8 (as suggested by the manufacturer), 9 or 10% Lumicyano solution is best for the development of fingermarks using four fabrics, using split grab marks and a range of sample ageing. Breaking down dye percentages for each fabric type, it was found that the mean score for black silk (1.65) and white (1.07) and black (1.33) polyester were, on average, enhanced with 10% dye while white silk had a higher average score with 9% Lumicyano (1.46), all of which is illustrated in Figure 3 (A full breakdown of all the results are available in the supplementary materials). When comparing the scores for each dye percentage for all fabric types, 10% Lumicyano had the highest mean score of 1.34, followed by 9% (1.26) and 8% (1.15), indicating that the former was the ideal percentage for the visualisation of fingermarks. Lumicyano (10%) exhibited brighter luminescence than 9% or 8% solutions, as would be expected, due to higher concentrations of incorporated dye (Figure 4), though at times 9% and 10% solutions had comparable brightness. However, observations indicated that many samples visualised with the 10% solution over-developed and obscured the detail of marks, despite its high scoring numbers. This might have implications for evidence when it is known or assumed that a print had been deposited long before development, as a 10% solution might allow for enhanced observation of a mark and easier targeting for further examination. In 31% of cases where visualisation was increased with a 10% solution, the largest impact was seen after 7 days of ageing. Archer *et al.* [35] noted that loss of squalene occurred in prints a little over a week old. Therefore it may be that the presence of squalene inhibited Lumicyano interaction and, only as the levels diminished, was Lumicyano then able to react positively with remaining residues. Moreover, about 63% of cases where visualisation was amplified occurred on black fabrics, which is most likely the result of a darker background providing greater contrast after a more luminescent Lumicyano had been applied. Consequently, a 9% solution is suggested for fresh prints while 10% might be more appropriate for visualisation of prints 7+ days old and on dark fabrics.

Figure 3. ***Mean and overall (all fabrics combined) mean scores of fabrics for each Lumicyano dye percentage***.

Figure 4. ***Study 1: Differing degrees of luminescence on white silk (Day 28, Donor 3).***

Of the fabrics tested, black polyester tended to develop highly visual, empty prints (mean score of 1.16), meaning there was no ridge detail to observe (Figure 5a). White polyester exhibited similar behaviour, but the background provided very little contrast in comparison, which would have influenced the grade. As polyester was smooth and of a tight weave it is thought that the finish coat and water-resistant properties may have influenced its ability to retain fingermark residues in detail. If the fabric has been washed and thus the possible finish coat and hydrophobicity diminished this could affect the level of detail observed, this will need to be examined in future research.

Average scores were used to rank a donor's ability to leave fingermarks on all four fabrics throughout all dye concentrations from 1 (being the best) to 6 (being the poorest) as follows: donor 3 (1.78), 5 (1.32), 1 (1.26), 4 (1.20), 2 (1.02), and 6 (0.91) by adding the total scores of each donor for fabric types and dye percentages. Fabrics were ranked according to their ability to retain fingermark residues across all dye percentages using their mean scores, with black silk (1.37) classified as the best, followed by white silk (1.34), black polyester (1.27) and white polyester (1.01). Nearly all samples (97%) in this study developed marks; however, considering that the highest possible score for a mark was 4.50, many did not afford sufficient detail for identification, such as in some grab marks developed more detailed palmprints whilst fingerprints were unidentifiable (Figure 5b). This can be attributed to the very nature of how the mark was deposited; whereby the action of a moderately forceful grab can often cause smudging. The frequency of fingermark scores for each fabric and for all studies in numerical and percentage values were calculated, and it was extrapolated that 52% of all graded fingermarks received a score of 0.75 out of a potential 4.50. Again, sorely lacking the required detail to make an identification yet sufficient for establishing regions for further examination, such as an area to target for DNA or in the form of intelligence gathering, such as corroboration of a sequence of events.

Figure 5. ***(a) Empty grab marks (Day 14, Donor 1, Black Polyester). (b) Varying mark detail between digits and palm (Day 7, Donor 3, Black Polyester).***

It would be expected that as time passed marks would become less detailed and, hence, less visible, as was observed by Fraser *et al.* in two separate studies [20, 30]. Nevertheless, the authors did concede that, on occasion, the trend deviated and more detail was visualised on older samples [20]. Archer *et al.* [35] confirmed that fingerprint composition changes over time due to decomposition, which may be the reason why detail was better visualised on older samples in the studies conducted by Fraser *et al.* [20, 30] and why the same trend was seen in this study (Figure 6). The overall fingermark scores dipped after 14 days for all fabrics then increased for black polyester and the silks for the remainder of the study. It was noted that when day and fabric type were the only factors considered, the polyesters yielded the highest mean scores at three days old while the silks achieved highest mean scores at 21 (white silk) and 28 (black silk) days. Therefore, this suggests that polyester fabrics favour shorter ageing periods for Lumicyano effectiveness and silks favour relatively longer ageing periods. This might be related to several factors, such as the thread count, thread thickness, weave or the hydrophilicity/hydrophobicity of a fabric. Since polyester has hydrophobic properties [4], it is possible that residues that interact strongly with Lumicyano may evaporate relatively quickly, as they cannot absorb into the material. Meanwhile, the fine texture, open weave and porosity of silk is ideal for absorption and allows the residues that interact with Lumicyano to resurface and evaporate much later. As a result, it might be advisable to age silks for longer periods while polyester type fabrics should be processed immediately. Findings such as these could wider implications for forensic examinations; a chart outlining ageing periods according to fabric type, properties, and priority number would help streamline examination, especially if resources were limited. Obviously, further investigation would be needed to create such a chart.

Figure 6. ***Mean score of fabrics for each Lumicyano dye percentage at all ageing periods.***

3.1.1 Statistical Analysis of Study 1

A generalised linear model was carried out using a cumulative logit link function for the dependent variable (Grade) which has a multinomial (ordinal) distribution. There were two continuous independent variables (day and dye percentage), and each fabric type was analysed separately to determine if either independent variable contributed to the grade determined. There was no significant effect of either ageing period (Day) or dye percentage on the development and visualisation of fingermarks for white polyester. However, dye percentage was found to have a significant effect on the development of fingermark in both black and white silk. Ageing period (Day) has a significant effect on the development of fingermarks on black polyester only.

Table 2. ***Results from a generalised linear model with a multinomial (ordinal) distribution for the dependent variable (Grade) and cumulative logit as the link function. Independent Variable (IV)1: = ageing period; Independent Variable (IV) 1 =: dye percentage. * indicates significant effect at 5% level***

Fabric	Test of model effects

Black PE	**Day:** Wald $\chi 2(1)$ =3.840; p =0.05* **Dye percentage:** Wald $\chi 2(1)$ =1.592; p =0.207 **Day* Dye percentage:** Wald $\chi 2(1)$ =3.383; p =0.066
White PE	**Day:** Wald $\chi 2(1)$ =0.107; p =.743 **Dye percentage:** Wald $\chi 2(1)$ =0.137; p =0.712 **Day* Dye percentage:** Wald $\chi 2(1)$ =0.238; p =0.625
Black Silk	**Day:** Wald $\chi 2(1)$ =2.128; p =0.145 **Dye percentage:** Wald $\chi 2(1)$ =9.036; p =0.003* **Day* Dye percentage:** Wald $\chi 2(1)$ =1.322; p =0.250
White Silk	**Day:** Wald $\chi 2(1)$ =2.128; p =0.145 **Dye percentage:** Wald $\chi 2(1)$ =9.036; p =0.003* **Day* Dye percentage:** Wald $\chi 2(1)$ =1.322; p =0.250

3.2 STUDY 2. HUMIDITY STUDY

In Study 2, split, six-series depletion fingermarks were used to assess the relative humidity (RH) in a fuming cabinet that would yield the best development of a mark. Eight different fabrics and an ageing period of 1 and 3 days were explored in this study, using Lumicyano and a dye concentration of 9%. This percentage was adopted as it was suggested in Study 1 that 9% be used for fresher prints and, additionally, attachment of 10% dye solution led to background fluorescence that obscured details. The use of 9% dye concentration avoids this and allows marks to be more clearly observed and graded.

In general, depletion scores ranked as expected due to the loss of residues, with the first depletion in the series scoring highest with most detail, while the last depletion in the series scored lowest (Figure 7). Figures 8 & 9 illustrate the mean scores of fabrics at each RH for both ageing periods and in both graphs it can be seen that viscose satin was the only fabric type on which fingermark residues did not develop for any donor at any time. This may be the result of its smooth, glossy surface, preventing the adhesion of fingermark residues. Satin acetate performed well overall after one day of ageing, but its performance declined with increased age, as did black silk. Generally, satin acetate, black and white silk and black polyester performed better than white polyester or nylon. However, their overall performance declined on older samples and polyester had an inclination to develop empty prints, where the residues have spread causing a solid white fingermark, with no ridge detail.

Figure 7. ***6-series depletion (Day 1, Donor 2, 77% RH [from left to right: white silk, black polyester, white polyester, satin acetate, cotton]. Six series fingermark was omitted from photograph to better capture detail of the visible five series fingermark, as there was no sixth fingermark observed).***

3.2.1 One day of ageing

Lumicyano on black silk saw an overall steady rise in mean scores from 75 to 80% RH after which performance declined. White silk yielded mean score marks graded 1.50 or above at 77, 78, 79, and 81% RH and mean scores below 1.50 at 75, 76, 80, and 82-84%. There was very little relative deviation of Lumicyano performance on black polyester (μ = 1.30, σ = 0.13) except for at 83 (1.47) and 84%, (1.00) which were significantly different from the other relative humidities. White polyester also saw little deviation across all relative humidities, with a mean score of 0.80, except that Lumicyano performed at a much lower grade range on white polyester than it did on black polyester. This is notable considering black and white polyester are of the same fabric type and weave yet differ only in colour. It is evident that different coloured backgrounds have a substantial impact considering black polyester had an average nearly double that of its white equivalent. Put simply; a white background yielded poor contrast compared to its darker counterpart. This could be due in part to the pigment or dye added to the fabrics to produce their colour, which in turn affected the polymerisation. Lumicyano on cotton fabric, like black silk, saw an overall steady rise from 75 to 80% RH, peaking at 80% RH and declining in performance beyond that. A possible reason for this might be, as Knighting *et al.* [31] suggest, that cotton absorbs residues, reducing the opportunity for Lumicyano to react with residues at the surface level. Mean score marks were graded 1.50 or above for all relative humidities on satin acetate except for an RH of 83 and 84%, at which point performance of Lumicyano declined. Lumicyano on nylon performed comparably to white polyester, which might again be attributed to its white background and similar properties (strong, water resistant and development of static charges) [4, 36-38]. Relative humidities of 77 and 82% were significantly lower than the average score of a developed mark (0.68).

Figure 8. ***Mean RH score of fabrics for day 1.***

3.2.2 Three days of ageing

The performance of Lumicyano on black silk was significantly reduced after three days of ageing, on average, scoring 0.88 across all relative humidities, with the poorest performance occurring at 75 and 83% RH. Lumicyano reached its peak performance on white silk at 77% RH on day 1; however, after three days of ageing peak performance was 78% RH. In this case, there was a gradual increase in mean score from 75 to 78% RH, averaging to a mean score of 1.60. This fabric saw a 9% increase in Lumicyano performance from day 1, which may be due to natural fluctuations in quality of residue depositions. Lumicyano experienced a 62% decrease in performance between one and three days of ageing on black polyester while an 85% decline occurred for white polyester. Fingermarks did not develop on cotton under the 75% RH condition; however, across all other relative humidities, there was an average mark score of 1.16.

Additionally, there was a 42% increase in performance of Lumicyano between both ageing periods. Relative humidities (76-78%) yielded the highest scoring averages for satin acetate. Meanwhile, 75% RH scored a mean of 0.25, significantly lower than the mean score of 1.37 across all relative humidities. Consequently, there was an 80% decrease in performance of Lumicyano between both ageing periods. There was only a 5% difference in mean scores between both ageing periods for nylon and interestingly, the three day ageing period resulted in a higher scoring mean. This increase is likely the result of inherent variations in residue quality and/or donor secretions.

Overall, 71% of samples resulted in a decrease of Lumicyano performance for fabrics for each donor between ageing periods. In the 29% percent of instances where this was not the case, white polyester from donor 1; white silk, cotton and nylon from donor 2; and black polyester, white polyester, and satin acetate from donor 3 saw an increase in Lumicyano performance. For both ageing periods of one and three days, the donors ranked from best to worst as the following: donor 2, 3 and 1. It should be noted that the two higher ranking donors also had fingermarks that saw an increased performance of Lumicyano after three days of ageing versus one. It may be that these two particular donors produce high levels of residues that extensively interact with Lumicyano or deposited residues that did not evaporate as quickly as compared to the other donor. Out of 1,440 total impressions, 81% developed marks after one day of ageing, while after three days, this percentage decreased to 74%. At first glance, it may appear that some humidities other than 80% visualise more detail on specific fabrics; however, no profound inferences can be made from such a small-scale study and, as such, it unreasonable to suggest that anything other than the recommended 80% be used unless future research determines otherwise. To determine the full impact of RH on fabrics additional donors, fabrics and a more comprehensive timeline should be investigated.

Figure 9. ***Mean RH score of fabrics for day 3.***

3.2.3 Statistical Analysis of Study 2

The analysis performed for Study 2 involved only the first fingermark in a depletion series for all donors, each humidity environment, and ageing periods (Table 3). Statistical analysis provides evidence that there was a significant interaction at the 5% significance level between the factor ageing period (Day) and the independent continuous variable RH (relative humidity) of the fuming cabinet for both black and white polyester. There were no main effects of either ageing period (Day) or relative humidity on the development of fingermarks on either black or white silk, cotton, satin acetate pr nylon. However, it has been shown in past studies [22] that RH does influence the enhancement of a mark (on non-porous substrates), which is why 80% RH is recommended.

Nevertheless, there did appear to be a significant main effect at the 5% significance level produced from ageing for both polyester fabrics, which contrasts the findings in Study 1 but does support findings from previous studies [20, 30]. However, main effects are difficult to interpret in the presence of an interaction which is the case here for both polyesters. Statistical analyses were not performed on viscose satin because no fingermarks were recovered.

Table 3. Results from a generalised linear mixed model ***for main effects and interaction of fixed factors day (factor1- 2 levels) and humidity (continuous independent variable) and donor as a random factor. Multinomial logistic regression for ordinal outcomes (Grade) was used with a cumulative logit link (ordinal outcomes)***

Fabric	Linear mixed model
Black PE	**Day:** F(1, 73) = 6.087; p = 0.016* **Humidity:** F(1, 73) = 9.570; p = 0.003* **Day* Humidity:** F(1, 73) = 6.544; p = 0.013*
White PE	**Day**: F(1, 54) = 4.992; p = 0.03* **Humidity:** F(1,54) = 0.024; p = 0..877 **Day* Humidity:** F(1, 54) = 4.588; p = 0.037*
Black Silk	**Day**: F(1, 111) = 0.026; p = 0.871 **Humidity:** F(1, 11) = 3.709; p = 0.057 **Day* Humidity:** F(1, 111) =0.05; p = 0.824
White Silk	**Day**: F(1, 92) = 0.47; p = 0.495 **Humidity:** F(1, 92) = 0.473; p = 0.493 **Day* Humidity:** F(1, 92) = 0.487; p = 0.487
Cotton	**Day**: F(1, 73) = 0.225; p = 0.637 **Humidity:** F(1, 73) = 2.559; p = 0.114 **Day* Humidity:** F(1, 73) = 0.197; p = 0.658
Satin Acetate	**Day**: F(1, 54) = 0.006; p = 0.938 **Humidity:** F(1, 54) = 2.176; p = 0.146 **Day* Humidity:** F(1, 54) = 0.001; p = 0.971

Nylon	**Day**: F(1, 92) = 1.257; p = 0.892 **Humidity:** F(1, 92) = 0.516; p = 0.203 **Day* Humidity:** F(1, 92) = 0.536; p = 0.831

3.3 STUDY 3. COMPARATIVE STUDY

Figure 10 clearly demonstrates that more marks were recovered on black silk in comparison to the other fabrics. As an enhancement technique, Lumicyano proved to obtain the highest mean scores except in the case of black silk, which achieved a higher mean score with the cyanoacrylate and subsequent BY40 addition method, as illustrated in Figure 11. Figure 12 shows the mean scores for fabrics at all ageing periods developed with each technique where the following remarks are graphically represented. In a study where 96% of prints developed, almost 50% of the time it was easier to visualise a mark on black silk with the addition of BY40, due to its dark background that provided contrast (Figure 13). On three occasions, this was also true for white polyester (after 28 days of ageing for donor 1 and after one day of ageing for donors 4 and 5 [Figure 14]). In all other instances, the subsequent addition of BY40, for both conventional CA and Lumicyano solution, either made no difference or worsened the detail of the mark. However, the addition of BY40 to white silk was absolutely detrimental to the visualisation of fingermarks, making previously visible marks indiscernible, as illustrated in Figure 15. This reduction in detail and, therefore grade, illustrates one of the advantages of using a one-step process, being that solvents are not required. With a two-step process, a dye is generally required, such as ethanol, which as demonstrated here has had a detrimental impact on marks observed. The most drastic downgrade occurred on a print deposited by donor 3 after one day of ageing where, before BY40 was applied, the score was 2.25 and dropped to 0 after. This differs greatly from the positive enhancement of sequential addition of BY40 to Lumicyano that Farrugia *et al*. [27] found for plastic bags. One possible explanation for the vastly different responses of each coloured silk to the addition of BY40 is the ability of silk to absorb dyes so easily [36]. It is possible that the black dye inhibited the complete uptake of BY40 dye or simply that the dark coloured fabric provided less contrast to visualise the yellow dye. Meanwhile, the white silk entirely absorbed the yellow colour, wholly concealing any fingermarks. A shorter application time of BY40 (in the range of a few seconds) or possibly even a spray technique might be considered in the future to address this issue. Possibly even the use of a different fluorescent dye altogether, such as basic red 14 or rhodamine 6G, might prove more effective. Though caution should be taken if applying those dyes as they pose a higher health risk than BY40. Nevertheless, the quality of Lumicyano performed best overall as it produced higher quality marks than conventional CA (supporting previous findings [25, 29]) while BY40 was destructive in many cases.

Figure 10. ***Mean score of fabrics for each development technique: Lumicyano (Solution & Powder), Lumicyano (Solution only) and no BY40, Lumicyano (No Powder) & BY40 and Traditional CAF (Cyanoacrylate & BY40).***

Figure 11. ***Development of all techniques on black silk (Day 1, Donor 1).***

Figure 12. ***Mean fabric scores at each day for all development techniques.***

Figure 13. **Black silk before (left) and after (right) BY40 application (Day 7, Donor 1).**

Figure 14. ***White polyester before (left) and after (right) BY40 application (Day 1, Donor 5).***

Figure 15. ***White silk before (left) and after (right) BY40 application ([a])Day 7, Donor 1, [b])Day 1, Donor 1).***

3.3.1 Statistical Analysis of Study 3

The results of the analysis (Table 4) for black and white polyester indicate that period of ageing (day) and development technique (dye), separately, influenced fingermark score at the 5% significance level. However, there was no interaction discovered between them. For black silk fabric, the period of ageing had an effect on fingermark score at the 5% significance level. Although, the development technique had no effect and no interaction was found between ageing period and development method. The analysis of white silk indicated that the development technique but not the ageing period, influenced fingermark score, and, there was no interaction discovered between the independent variables.

Table 4. ***Results from a generalised linear model with a multinomial (ordinal) distribution for the dependent variable (Grade) and cumulative logit as the link function. The model has one continuous independent variable (ageing period – day) and one factor (dye development technique). The ageing periods were between 1 and 28 days, and the development techniques were Lumicyano (solution + Powder), Lumicyano (solution only no BY40), Lumicyano (no powder) + BY40, Cyanoacrylate + BY40. Main effects of the independent variable and the factor and the interaction between the factor and independent variable are reported. * indicates a significant effect.***

Fabric	Generalised Linear Model Results Test of Model Effects
Black PE	**Day:** Wald $\chi 2(1)$ =32.935; $p < 0.001$* **Dye:** Wald $\chi 2(3)$ =15.443; p =0.001* **Day* Dye:** Wald $\chi 2(3)$ =2.707; p =0.439
White PE	**Day:** Wald $\chi 2(1)$ =14.383; $p < 0.001$* **Dye:** Wald $\chi 2(3)$ =9.812; p =0.020* **Day* Dye:** Wald $\chi 2(3)$ =0.840; p =0.840
Black Silk	**Day:** Wald $\chi 2(1)$ =7.755; p =0.005* **Dye:** Wald $\chi 2(3)$ =1.165; p =0.761 **Day* Dye:** Wald $\chi 2(3)$ =0.899; p =0.826
White Silk	**Day:** Wald $\chi 2(1)$ =2.419; p =0.120* **Dye:** Wald $\chi 2(3)$ =12.760; $p<0.005$ **Day* Dye:** Wald $\chi 2(3)$ =2.286; p =0.515

4 CONCLUSIONS

Three studies to examine the interaction of Lumicyano on different fabrics under altered conditions were conducted to better understand the behaviour of this one-step cyanoacrylate. According to statistical analysis, there was some influence of age (all studies) and dye percentage (Study 1), RH (Study 2) and development method (Study 3) on fingermark visualisation or scores. Moreover, there was often no interaction between two factors. The exceptions to this in Study 2 were for black and white silk. Exceptions for Study 2 included an effect on fingermark score due to period of ageing for black and white polyester. Study 3 saw exceptions for black silk, where aging period was found to influence fingermark score, with age and development technique (individually) affecting fingermark score on black and white polyester and ageing period affecting development of fingermarks on white silk. As the grading scheme is quite subjective, it is expected that the data and tests are not entirely compatible. However, this should not negate the observations made throughout the studies.

Lumicyano (9%) was interpreted as the optimal percentage to be used for developing prints in Study 1, due to enhanced mark visualisation and lack of background fluorescence obscuring detail. This contradicts both what the manufacturer recommends (8%) and what statistical analysis suggests (10%) as the ideal percentage. This underscores the subjectivity of fingermark grading post-enhancement and, additionally, highlights the need for experience and knowledge. This experience can prove vital to identifications, rather than relying solely on computer programmes and statistics. Study 2 neither reaffirmed nor rejected the recommended RH of 80% as ideal for most substrates, including fabrics. Consequently, more testing is required to determine whether there is a general RH recommended for all fabrics or if certain fabrics are more suited to specific relative humidities. In complete contrast to what Farrugia *et al.* [27, 28] discovered, Study 3 established that the sequential addition of BY40 to either traditional CA or Lumicyano is comparable in quality to Lumicyano on its own or reduces the value of the mark, if not erasing it completely. Black silk and, occasionally, white polyester were the exceptions to this finding. Overall, it is recommended from these findings not to use BY40 on porous substrates such as fabric. These observations can help inform decisions made when processing clothing from scenes of incidents; for cold case material, it is advantageous to know that higher dye percentages might better enhance aged marks and it is valuable to understand that sequential addition of BY40 to even the same type of fabric can yield opposing outcomes. There should also be an expectation with recovery on fabrics involving struggles, as simulated in this study, that often there be limited detail observed. This is due to the actions taken when "struggle" marks are placed on the fabric, and that fabric is classed as a difficult substrate for fingermark visualisation. Therefore the low grades of 0-2 which have been found here and in others [30, 31], should not be unusual or unexpected.

This study was limited by a lack of variety of fabrics; only two types of fabric (two colours each) were examined for Studies 1 and 3. Within each fabric type there can be a range of quality, texture, weave, added dyes, patterns, and fabric mixes, so it is important to consider this when including additional fabric in the future. Cotton, being a commonly worn fabric, should be examined further since it is a fabric type likely to be encountered in many operational investigations. Including more donors is essential for arriving at substantial results beyond preliminary observation. The inclusion of highly aged print (i.e. 1+ years) could shed light onto residue changes over time and aid in developing processing techniques for cold case material. Introducing scanning electron microscopy (SEM) into future research might prove beneficial to determine how and what type of polymers form on fabrics and whether different techniques promote formation of different varieties. Also, it might be worthwhile to reconsider the method of BY40 application due to the porous nature of fabrics and their potential to absorb more than non-porous samples. Regarding BY40, black silk should be explored further as it behaved quite differently to other fabrics investigated. Lastly, in these studies, all marks were graded by one individual and verified by a second fingermark researcher. In future studies, a fingermark identification expert will review grades to calibrate the scores. Eventually, a consistent, objective grading scheme needs to be created to better evaluate fingermarks in all research and make meaningful conclusions. The development of such a tool would refine fabric-related examination and produce consistent reporting.

Studying the effectiveness of Lumicyano on different fabric types should continue to be investigated as there are advantages to this system. Although Lumicyano has a greater cost than traditional CA, it reduces the man hours spent on examination and, in effect, makes Lumicyano more economical. From observations in this study, Lumicyano may also curtail potential loss of ridge detail from the use of solvents in a sequential dyeing stage. This is turn could impact on real life cases where fabric is involved as evidence. The choice of visualisation technique decided upon may be influenced by the fabric type of evidence, one fabric may be better suited to visualisation with Lumicyano while another fabric type may lead to enhanced visualisation with VMD or another fingermark enhancement technique. As for further evaluation of Lumicyano, it might be useful to investigate fingermark development on different fabric types combining Lumicyano and vacuum metal deposition. Vacuum metal deposition is resurfacing as a useful method to develop fingermarks on various substrates and has been touted as an effective tool. Current and previous studies have demonstrated that Lumicyano has promise as an alternative or replacement to investigative laboratory protocol. As such, this simple, one-step CA deserves further evaluation.

The following are the supplementary data related to this article.

Table S 1. ***Fingermark score frequencies for all studies (number of marks on top with percentage below in brackets). 1 = Study 1, 2 = Study 2(first of six series depletion used for analysis), & 3 = Study 3(Lumicyano solution only without BY40 also included in analysis of results). Black polyester missing 2 samples due to human error preventing grading.***

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Highlights

- Nine percent Lumicyano is the optimal dye percentage for developing and visualising fingermarks.
- Lumicyano is a superior method for fingermark visualisation than the traditional two-step method.
- A one-step Lumicyano application on fabrics performs better than as a two-step process.
- Sequential addition of Basic Yellow 40 is generally not recommended on the use of fabrics.